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Overview of Black Start Provision by Offshore Wind Farms

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***Abstract*—Thanks to the solid standards and principles of design and restoration planning after a blackout, power systems in developed economies generally show a high level of resiliency. Nevertheless, this power system restoration practice strongly relies on conventional power plants, e.g. large thermal power plants. As future global goals aim at reducing the use of fossil fuels and lowering carbon-dioxide emissions, conventional power plants are often taken out of operation. These are characterised by slow start-up times and considerable use of fossil fuels. In this context, large offshore wind farms (OWFs) show potential as renewable-based black start (BS) service providers. These can be equipped with a self-starter, e.g. synchronous generators or innovative power-electronic-based converters, such as battery energy storage systems (BESSs) and/or grid-forming wind turbines in order to BS the system. Additionally, state-of-the-art complementary devices such as STATCOMs or synchronous condensers can help with dynamic regulation and support the OWF both in island operation and BS. In this paper, an overview of different system configurations for OWF BS is presented. Firstly, the requirements for BS from non-conventional power plants are outlined. Afterwards, the challenges faced by OWFs to fulfil these requirements are identified. Finally, different solutions for system configuration to equip OWFs for BS are proposed.**

***Keywords*—black start, power system restoration, offshore wind farms, power system resiliency, grid-forming, island operation**

I. INTRODUCTION

The gradual replacement of conventional power plants by renewable generation is raising new challenges to the resiliency and planning of operations of an almost 100%-renewable future power system. In this context, it is essential to rethink restoration strategies, as currently these strongly rely on conventional power plants, e.g. large thermal and hydroelectric power plants. As future global goals aim at reducing the use of fossil fuels and lowering CO_2 emissions, fuel-based conventional power plants are often taken out of operation. It is thus crucial to use all technologies available in the power system with the capability to provide fast support [1]. Large offshore wind farms (OWFs), with their extended capacity, show potential as being fast and environmentally friendly renewable-based black start (BS) service providers [2].

BS is the procedure of restoring a part of an electrical grid to operation without relying on the external transmission network to recover from a blackout [3]. A BS-service provider may be a single unit or a plant, it could also consist of an aggregation of sites, which operate as a single unit providing restoration service [4]. Therefore, the OWF itself can be regarded as the BS-service provider. Once this is achieved, the whole or a part of the OWF is energised. This is thus working in island operation, using local generation to balance its load requirement as a wind farm (WF) power island. Power system restoration represents the actual procedure of energising the transmission network, from a state of no power to a state of fully normal operation comprised of all loads and generation units. In particular, the procedure of block loading concerns the energisation in blocks of loads of the transmission system. At this stage, the OWF has formed a BS power island, having energised its system and part of the network. After establishing a BS power island, the synchronisation with other energised islands of the transmission network will take place. Finally, the transmission network will be fully restored [4]. This process is illustrated in Fig. 1.

Besides the purpose of system restoration itself, island operation of OWFs is also important. When an offshore wind turbine (WT) is out of power for more than one day, threats to its integrity may emerge. For example, moisture damage in the nacelle of the WT due to low temperatures and condensation. Another concern is the icing up of the blades and/or measurement equipment. All these threats result in the use of external/mobile auxiliary power units to supply the WTs with emergency power for auxiliary loads and components. Use of these auxiliary units can be reduced or totally avoided since OWFs can produce power to sustain themselves if there is wind, which is often true for offshore systems [5].

ENTSO-E, European network of transmission system operators (TSOs), included BS and island operation as optional requirements, for both alternating current (AC) and high-voltage direct current (HVDC) connected OWFs [6]-[7]. Furthermore, different TSOs propose to research on the BS capabilities of renewable sources, including OWFs [8]-[10]. Moreover, BS is a crucial and extra service that is agreed separately from ancillary services. Thus, it is additionally paid, enhancing the revenue in operating OWFs.

The rest of this paper is organised as follows: the overview of current and extended system requirements for BS provision is given in Section II. Then, the identified challenges for OWFs as BS service providers are presented in Section III. Different strategies for new OWF configurations are outlined in Section IV. Finally, discussions and concluding remarks are given in Section V and VI.

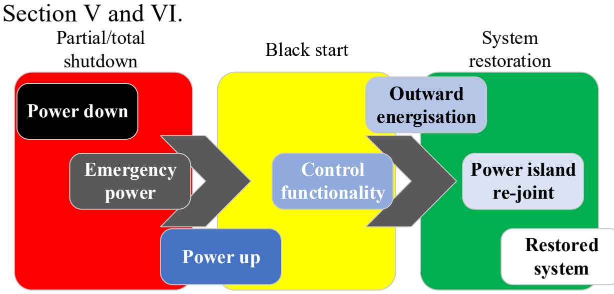

Fig. 1. Principal stages of black start and power system restoration [4].

II. Requirements for Black Start Provision by Offshore Wind Farms

BS requirements do not apply to OWFs at present. OWFs differ from conventional BS sources as these are power-electronic-based systems whose power source is fluctuant. Nevertheless, some TSOs are studying new possible sources of BS [4],[11]. Thus, also an extended set of requirements has been proposed. These have been studied separately by ELIA and National Grid ESO (NGESO), i.e. Belgium and Great Britain TSOs respectively. These requirements are the following.

a) Self-Start: This is the ability to start-up the main generating unit of the station without the use of external power supplies.

b) Time to Connect: This is the time taken to start-up the BS unit once received instructions from the TSO. This requirement is 2 hours for NGESO, the same as for established conventional generation sources. The potential brought by OWFs could lower the needed time, hence contributing to a faster restoration. ELIA sets a time frame of 1.5 to 3 hours based on the location of the BS provider.

c) Service Availability: The ability to deliver the contracted BS service. ELIA sets the availability requirement as a contractual term for the specific BS provider. As a general minimum requirement, the acceptable unavailability for maintenance is set to be maximum 40 days per year. This is required to be over 90% of the year for NGESO, which is the same requirement as for conventional generation.

d) Voltage Control: The ability to control voltage level within acceptable limits during energisation/block loading. In this case, it is interesting to compare the requirements by the two TSOs. NGESO requires simply ±10% of the rated value. Conversely, ELIA has set the requirement in connection with block loading. This is shown in Fig. 2. During the first 2 s after block loading inception, the voltage range is up to 70% of rated value, i.e. 30% deviation. After 2 s, the range is lowered to 15% variations. After 12 s, the acceptable deviation is 7.5%. Therefore, the requirement imposed by ELIA is initially more flexible, while becomes stricter than NGESO's when transient phenomena should be settled.

e) Frequency Control: This is the ability to manage frequency level when block loading. In this case NGESO requires 47.5-52 Hz, while ELIA has specified 49-52 Hz.

f) BS Service Resiliency of Supply: This is the minimum time the provider should deliver the contracted service once instructed to BS. NGESO specifically created this requirement for non-conventional generation, setting the value to at least 10 hours.

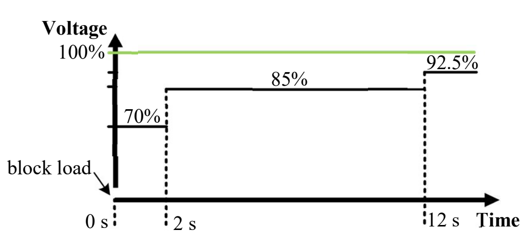

Fig. 2. Acceptable voltage range required by ELIA [11].

TABLE I. Comparison of New Requirements for Black Start.

Requirement	***National Grid ESO***	***ELIA***
Time to connect	⩽2 h	1.5-3 h
Service availability	⩾90%	Dependent on the BS unit
Voltage control range	±10%	Time based (see Fig. 2)
Frequency control range	47.5-52 Hz	49-52 Hz
Block load	20 MW	10 MW
Inertia provision	800 MVA.s	/

g) BS Auxiliary Unit(s) Resiliency of Supply: This is the ability to run continuously at the output required to support/deliver the contracted BS service for a minimum of three days, set by NGESO.

h) Block Loading Capability: Capability to accept instantaneous loading of demand blocks. This requirement was set to 35-50 MW for conventional generation by NGESO. When extending the service provision to renewable energy, the block loading requirement is lowered to 20 MW. For ELIA this requirement is set to a minimum of 10 MW.

i) Reactive Capability: This is the capability to energise part of the passive transmission network (Mvar>0, MW=0). This capability will depend on the local system configuration, but a capability of at least 100 Mvar exported from the WF should be met for NGESO. ELIA sets a different Mvar requirement for the specific BS zone only in procurement phase. The generator must also be capable of withstanding the magnetic inrush and transient voltages associated with this energisation.

j) Sequential Start-Ups: Ability to perform sequential start-ups. For both ELIA and NGESO, the requirement is at least three.

k) Short-Circuit Level (following the start of a system disturbance): This is the injection of reactive current I during a disturbance. NGESO has set this dependent on time t, as given in (1).

$$\begin{gathered} t \leq 80 \text{ ms:} \\ I \geq \frac{240\,[\text{MVA}]}{\sqrt{3}\cdot U}\,[\text{kA}]; \\ t > 80 \text{ ms:} \\ I \geq \frac{100\,[\text{MVA}]}{\sqrt{3}\cdot U}\,[\text{kA}], \\ U \equiv \text{connection voltage [kV]} \end{gathered} \tag{1}$$

l) Inertia Value: This is the stored rotating energy in the system. This is a requirement introduced only by NGESO specifically for non-conventional generation. It is set at 800 MVA.s and it could be either real or virtual.

A comparison of the most relevant requirements given by ELIA and NGESO is shown in Tab. I.

III. Identified Challenges

Since OWFs have not been designed with the purpose of restoring a black network so far, many new challenges arise in their design and operation. The main challenges identified are listed and explained below.

A. *Self-Start Capability*

Common OWF design does not include any self-start source. Usually, the energisation power comes from the transmission grid. Such a system is typically only equipped with grid-following (GFL) WTs, which are able to deliver power to an energised grid [12].

Therefore, a first challenge is to implement a self-start unit in the OWF. This could be a synchronous generator, powered by diesel or biomass, or a grid-forming (GFM) unit, if power-electronic-based. GFM converters can set the voltage magnitude and phase reference, thus forming the local grid [12]. Examples of GFM units can be battery energy storage systems (BESSs) or WTs.

B. *Service Availability*

Another challenge is posed by the availability requirements. For conventional generation, periods of unavailability to BS concern maintenance and/or planned outages. These do not consider the availability of the power source. For renewable generation, wind in this case, the fluctuation characteristics of this source may threaten the availability requirements set. According to [4], aggregations of wind generators can reliably deliver a sustained constant level of power, even for relatively long periods of up to five days. Nevertheless, this should be evaluated for each single site. Typically, a high level of availability requires the use of stored energy. In renewable-based power systems, this will imply using energy storage units, which represent an added cost. Lower availability requirements would reduce the need of combining renewable energy sources together with storage, which will lower the costs, and increase diversification in the BS market.

C. *Inertia Provision*

As power-electronic-based systems, OWFs are also challenged by the inertia requirement. As stated by NGESO, this could be either real or virtual. Therefore, more options are available in terms of system configuration, as both synchronous machines and inertia emulation control could achieve the set requirements.

D. *Control, Stability and Interoperability*

The novelty of operating the OWF as island and BS unit brings new opportunities for control and interoperability. Due to the similarities in operation, control schemes may be adapted from microgrid BS [13]. In case of power electronic devices, the interoperability of all devices, also GFM and GFL converters, needs to be designed carefully. Additionally, power converters can be operated as grid-supporting, i.e. participating in the regulation of the grid voltage amplitude and frequency by controlling the active and reactive power delivered to the grid [12]. Thus, innovative control strategies need to consider this novel OWF system operation. Consequently, stability also represents a challenge as, usually, an OWF is energised via the transmission grid, which is generally a strong grid. The OWF becomes more prone to instability in weak or no-grid conditions. This is especially complex with many power electronic sources connected to shore via extra-long AC cables.

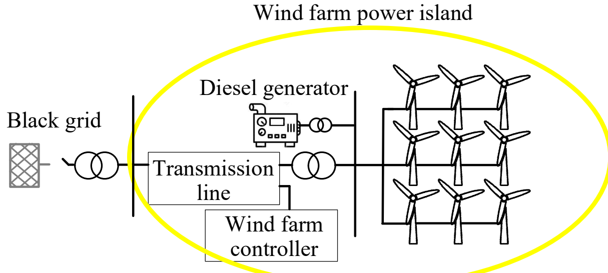

Fig. 3. Wind farm power island with diesel generator connected to the offshore substation.

E. *Transient Behaviour*

Transients during system restoration represent a difficult part of the BS procedure. A first challenge is represented by the WF power island energisation. To contain the energisation transients, novel energisation methods such as soft charging can be applied if GFM units are used.

Soft charging is the method whereby the power electronics within the GFM units are used to control the energisation process as the cable network is charged. Compared to sequential energisation of the single devices and passive components, soft charging has the advantage of containing transient phenomena. Furthermore, challenging transients may arise when energising the transmission network.

F. *Harmonic Performance*

The combination of different power converters, long AC cables and other passive elements introduces also issues for the harmonic performance of the system. This is due to the harmonic resonance of the system, which may be excited during the restoration procedure. Therefore, the analysis of the BS strategy needs to consider this challenge to mitigate the possible effects of harmonic distortion.

G. *Communication Settings*

Communication systems could also represent a challenge in the design of OWFs with BS capabilities. These should have appropriate flexibility to operate interconnected to the upstream network or autonomously during BS and island operation. To improve the system resiliency, communication could be avoided by regulation of the electrical quantities, e.g. frequency and voltage operated in a droop configuration.

IV. Offshore Wind Farm Configuration Strategies

In the state-of-the-art literature, several different system configurations have been proposed for a WF BS. As presented in § III, a main unit able to self-start needs to be incorporated into the OWF to be able to start-up the OWF and BS the grid. An overview of these configurations will be presented differentiating between the main self-start unit. Additionally, the use of complementary components, i.e. synchronous condensers and STATCOM, will be reviewed.

A. *Use of Synchronous Generators*

Some conventional power plants have small diesel generators to provide BS. These can be used to be able to start larger generators, which in turn will start the main power plant generators. In OWFs, usually the offshore substation (OSS) is equipped with a diesel generator, both in AC- or HVDC-connected OWFs [5]. This can provide power for the auxiliary components of the substation and start-up. This could also be exploited for BS purposes.

As described in [14], a diesel generator located in the OSS can firstly energise only one or a group of WTs. Afterwards, the WF power island is formed disconnecting also the diesel generator. This procedure is coordinated by an OWF controller based on centralised communication between the OWF controller and WTs. This is illustrated in Fig. 3. The method is applicable to both AC and HVDC systems. Nonetheless, no details about the control and interoperability of the full plant are elaborated.

In [15], a mobile diesel generator located offshore is used as the main reference source in the BS process to provide stable voltage magnitude and frequency for the island system. A STATCOM is used for voltage/reactive power V/Q support to the system.

A diesel generator could be placed on the single WT. In [16], a small diesel generator is located inside one or few of the WTs in the OWF. This will be used for the WT self-start. Afterwards, the OWF controller coordinates the voltage phase angle and/or magnitude setpoints for the self-started WTs. The OWF controller can start based on its own local uninterruptable power supply (UPS). Island operation without any diesel generator or external grid is discussed. Nevertheless, no details about parallel operation of the WTs are given. In [17], a method for controlling a WT that comprises an internal generator is presented. This is mainly related to the self-sustain of the WT to avoid damage. Wind forecasting is applied in order to optimise this functionality.

A diesel generator represents a resilient BS source, able to provide naturally inertia to the system. Furthermore, this and its fuel consumption in an OSS would have negligible cost. Nevertheless, its existence per se increases the costs.

A WF designed for BS containing combustion gas turbine generator and STATCOM for V/Q regulation is proposed in [18]. In this configuration, the generator provides the initial power for the WF, and then goes out of operation. STATCOM improves the reactive power control capabilities during BS and the WTs by undertaking frequency and voltage control. With high flexibility and reliability, combustion gas turbines can start up quickly in the absence of external power supply and provide continuous and stable power support for the WF.

To support the future renewable goals, an alternative to fossil fuels can be biofuels, e.g. biomass. Biomass generators can provide many of the same services as conventional BS providers. Nevertheless, this is typically on a smaller scale and, this must be considered carefully when setting technical requirements and levels of service [4].

B. *Use of BESS*

Another option, which is having an increasing trend in applications, is the use of storage, e.g. BESSs, hydrogen electrolysers, supercapacitors and more applications linked to renewable energy. In particular, BESS can be the GFM unit of the system [19]-[20]. This can be placed centralised or decentralised, as shown in Fig. 4. In OWFs, a centralised unit could be placed either onshore or offshore. A decentralised BESS could be small units placed in the single WTs.

In terms of comparison, decentralised BESSs offer higher system reliability, as the failure of one BESS does not prevent the system to BS. As presented in [14], keeping the same

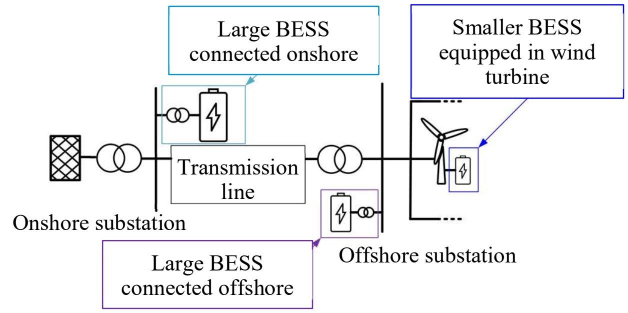

Fig. 4. Battery energy storage system (BESS) configurations in an offshore wind farm for black start provision.

structure seen in Fig. 3, the self-starter can be a BESS instead of a diesel generator. In [21]-[23], the use of a centralised BESS for WF BS is discussed. This can be a large unit located in the offshore substation. This has the advantage of adding flexibility to the OWF, storing energy during high wind conditions, and providing energy during low wind, i.e. increasing the system BS availability. Furthermore, innovative strategies for energisation, such as soft charge, can easily be implemented thanks to its converter technology.

A BESS does not provide inertia naturally. Nevertheless, GFM control can incorporate inertia emulation loops, such as virtual synchronous machine (VSM) control [24]. This has been applied in [25], where 30-MW GFM BESS is used in combination with an onshore WF. This technology together with VSM control is used to strengthen the grid by providing inertia, high fault current and fast power injection. Furthermore, a BESS can provide competitive market services while working in normal operation. This provides added revenue to the OWF. There is the possibility of locating decentralised BESS in the WTs. As a matter of fact, a comparison of different configuration for OWF BS enabled by BESS is given in [26]. In these results, the optimal system comprises of decentralised BESS units located in the WTs. In [27], a small energy storage, e.g. a BESS, is located in a WT for BS. Details about the WT structure, its software and the method for start-up are presented. However, any details about parallel operation of WTs during island mode are not given.

C. *Use of WTs*

Usually, WTs are equipped with internal power supply, like a UPS. This can help the WT to supply critical components such as internal lights in the tower and nacelle, aviation obstruction lights, controllers and switchgears for less than an hour. In this context, the internal power supply could be used to self-start the WT and BS the grid. Additionally, GFM WTs have the advantage to have a full power-electronic interface, which can be controlled to soft-charge and provide virtual inertia.

Island operation and BS for HVDC-connected OWFs using GFM WTs is particularly useful when the offshore converter is a passive unit, such as line-commutated converter or diode rectifier. This is discussed in [28]-[29], where the WTs form the grid offshore and BS the offshore diode rectifier unit to restore the onshore grid.

TABLE II. OVERVIEW OF DIFFERENT DEVICES FOR OFFSHORE WIND FARM BLACK START.

	Synchronous generator	*BESS*	*Wind turbine*	*STATCOM*	*Synchronous condenser*
Application	Self-start, dynamic compensation, overloading capabilities	Self-start, fast dynamic compensation	Self-start, fast dynamic compensation	Fast dynamic compensation and voltage recovery during faults	Dynamic compensation and voltage recovery during faults, overloading capabilities
Availability	Dependent on fuel	Dependent of stored energy	Dependent on wind	/	/
Inertia provision	Real	Virtual	Virtual	Virtual	Real

In [30], WTs are proposed for the island operation of a WF without any additional equipment. The operational WT thus acts as an auxiliary power supply itself. The method provides an efficient and cheap way of supplying power to an islanded group of WTs. Similarly, practical experiences with operating GFM WTs which do not present any additional equipment are presented in [31]-[32]. An onshore WF comprising of 23 WTs has been operated in VSM GMF mode for six weeks. Results show that WTs were able to respond appropriately to the inertia levels configured to all type of events. Higher level of performance would be possible, and suggestions span from adding energy storage, either within the existing turbine DC bus, or as a separate parallel converter.

As a matter of fact, the combination of BESS and GFM WTs would be a resilient proposal to fulfil BS requirements. Even though a BESS has a non-negligible cost, its application can further increase the revenue of operating OWFs. Moreover, a storage unit increases the availability of the power, as a minimum stored energy level can be guaranteed in all conditions. Furthermore, not all the WTs in an OWF need to be GFM. Adequate island and BS operation can be achieved with less than 25% GFM power in respect to the OWF size [33].

D. Complementary Devices

In addition to the self-start unit, the complementary use of auxiliary devices can increase the resiliency of the OWF as BS provider. Usually, STATCOMs are used for V/Q regulation. Furthermore, there is the possibility to control a STATCOM as a VSM for inertia emulation [34]. This has the advantage of having a full controllable unit which can have a fast response to support the system. Additionally, STATCOMs are devices that form part of a common OWF design. Thus, no further design costs are included. Synchronous condensers can be also considered for both inertial support and V/Q regulation in an OWF. Thanks to their inherent capabilities as synchronous machines, they can support the inertia requirements [35]. The effect is naturally less compared to a conventional synchronous generator, as its shaft is not connected to anything and spins freely [36]. Therefore, there is no effect of the rotating mass of the prime mover. In fact, the typical inertia constant of large synchronous condensers can be easily provided by a small storage unit, e.g. supercapacitor or BESS [37]-[39]. Even though time considerations need to be implemented. A supercapacitor might be able to deliver the energy to stabilise the system but its time constant plays a major role in the ability to stabilise networks. On the contrary, the effective STATCOM inertia constant is dependent on converter rating and can be varied by changing the gain constant of the inertial response. Nevertheless, a significant advantage of synchronous condensers is their overloading capability under various conditions in the system in terms of voltage [40]. Thus, it needs to be considered with the overall system characteristics. In [41], a case for using synchronous condenser to improve the system short-circuit power is presented. Improvement in fault-ride-through performance in terms of higher retained voltage and faster voltage recovery is demonstrated.

V. DISCUSSION

A comparison of the different devices discussed is shown in Tab. II. As it can be seen, there are different possibilities to overcome the challenges listed in § III. Conventional units, such as diesel generators, can be used for self-starting of the OWF. This is a proven technology, which is already present in OWFs. Its new application to BS needs could be advantageous but needs further research. For future 100%-renewable power systems, the implementation of BESS and/or GFM WTs as self-starters seems to be a valuable path forward. The use of a centralised BESS for BS has been proven successful. Nevertheless, the interoperability of GFM units could be challenging. Availability concerns do not support only the use of GFM WTs, as their power supply depends mainly on the wind and small storage. The complementary use of a large BESS together with GFM WTs or a mix of GFM and GFL WTs seems to be an interesting path forward for the research on OWF BS. This will achieve higher availability than having only GFM WTs, and higher revenue due to the several ancillary services that BESS can supply. Nevertheless, the control and interoperability for the OWF needs to be designed, especially focusing on GFM control and inertia emulation. In the absence of large-inertia conventional units, the converters will have to take care of the synchronization between WTs in order ensure voltage and frequency stability in the system. This could be done by having a master GFM unit, such as a large BESS, and GFL WTs as slaves. The use of complementary devices such as a synchronous condenser and STATCOM can help with fast regulation and support the OWF, both in island mode and BS. STATCOMs in the restoration procedure are particularly advantageous as this is already present in common OWFs, and it can be controlled to support the system inertia. Thus, serving both for voltage and frequency stability purposes.

VI. CONCLUSION

An overview of the current status of OWFs as BS service providers has been presented in this paper. The analysis is based on the state-of-the-art literature and OWFs system considerations. This study reveals that OWFs BS service provision is possible for OWFs with many different system configurations. The option of having a hybrid GFM system, comprised of BESS, GFM WTs and STATCOM seems an advantageous option. Nevertheless, new technology brings simultaneously new challenges with respect to design, control and interoperability, which were not seen before, either in the OWF itself nor between OWF and the grid. Thus, more research needs to be performed, especially on GFM control, its performance and inertia emulation.

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